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STUDY OF AUTOMATIC CONTROL SYSTEMS
FOR HELICOPTERS

FINAL REPORT ON PHASE I

31 July 1953

P. Wassett
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MINNEAPOLIS
Honeywell

Aeronautical Controls

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Security Information

STUDY OF AUTOMATIC CONTROL SYSTEMS FOR HELICOPTERS

FINAL REPORT ON PHASE I

M-H Aero Technical Report AD 5143-TR8
Contract Nonr-929(00)

31 July 1953

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By direction of
Chief of Naval Research (Code 461)

Aeronautical Research Department, Aeronautical Division
Minneapolis-Honeywell Regulator Company
Minneapolis, Minnesota

FOREWARD

This report was prepared by the Research Department, Aeronautical Division, Minneapolis-Honeywell Regulator Company, in accordance with the requirements of Navy Contract No. Nonr-929(00), administered by the Office of Naval Research. The contract was initiated under the research project identified by Expenditure Accounts 46000 (Research Navy) and 46832 (Aircraft and Facilities Navy). This is a contract for research involving the study of helicopter control systems from the point of view of automatic control of attitudes and power. Phase I of this study(for which this is the final report) has been supported by the above contract, which commenced on 15 June 1952 and expires on 31 July 1953. It has been proposed that the next phase of research under this program be supported by the Navy under a continuation of the Nonr-929(00) contract, beginning 1 August 1953.

ABSTRACT

Under Phase I of the Study of the Automatic Control Systems for Helicopters, the foundations were developed for the analytical determination of automatic control system design criteria. These foundations consist primarily of the theoretical equations describing (1) the transient motion of a hovering, single-rotor helicopter with rotor RPM degree-of-freedom, and (2) the dynamical characteristics of reciprocating and single-spool turbo-prop engine types. In addition, the mechanization of the control system transfer function has been investigated from the view-point of incorporating in the dynamical analysis the characteristics of high-performance components requiring a minimum of additional development.

Also discussed here are several topics remaining under investigation or otherwise not completed at the Phase I termination date (31 July 1953). These include the study of forward-flight transient motion, the initial phases of the complete closed-loop control study, and the REAC study of rotor RPM control in hovering for the case of the turbo-prop engine.

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I INTRODUCTION

The general task with which the present research program was initially confronted was the determination of desirable closed-loop transfer functions for helicopter automatic control systems. These systems were to be of the pilot-relief variety and were to perform the functions commonly associated with an autopilot and a rotor (or engine) RPM governor. While helicopter autopilots and RPM governors were in existence prior to the inception of this study, it had not been determined whether the designs of these controls were optimum from the standpoint of the net performance of the helicopter. In particular, it appeared that previous developments had ignored the possible inter-relationships between transients in rotor RPM and rolling and pitching motions of the aircraft. It was therefore indicated that a study be made to establish the criteria for the design of high-performance automatic control equipment for helicopters, with emphasis on the possibility of integrating the action of autopilot and rotor RPM governor.

The helicopter configuration chosen by mutual agreement for initial consideration under this program was the single main-rotor type with the torque-compensating tail rotor, and powered by a single-spool turbo-prop engine. In accordance with the aforementioned objective of studying the effects of cross-coupling between transients in rotor RPM and helicopter motions on the design and operation of automatic controls, it was necessary to develop the theoretical equations for the dynamical analysis on this basis. As for the turbo-prop engine, it was necessary to establish the acceleration characteristics for the particular unit chosen as the investigation model.

An additional consideration at the outset was the desire to explore the value to the present study of the comparatively new Root Locus method of feedback analysis. This technique was applied in the investigation of rotor RPM control based on relatively simplified flight conditions (see Section V). Of course, also available at Minneapolis-Honeywell as a tool for the analysis of closed loop servo systems, is the REAC analog computer, which was employed in the same investigation as above.

The program of study experienced several alterations in schedule from that originally set up. These had to do primarily with the interest expressed by the Bureau of Aeronautics mid-way in Phase I in having this work give early consideration to the control problems of the helicopter with reciprocating engine, especially for the ASW-type of mission. The effort on the turbo-prop engine was consequently suspended prior to completion. The theoretical determination of the dynamical characteristics of the piston-type engine was then undertaken

simultaneously with efforts to secure corresponding experimental data from the Aeronautical Engine Laboratory, Naval Air Material Center.

With the development of the equations of motion for the helicopter and the theoretical estimate of the transient behavior of the reciprocating engine, the servo analysis was initiated by a detailed consideration of the means for mechanizing the error sensing, control actuating, and other elements of the closed-loop feedback systems. The status of this work is included in the discussions of Section VI.

The preceding statements were intended to provide an overall picture of the program of activities in Phase I of this study. The sections to follow will discuss this work at greater length, although those topics for which Interim Reports have been issued are only briefly described here.

II REVIEW OF PRIOR ART

2.1 STUDY OF THE LITERATURE

2.1.1 Basic Helicopter Dynamics

A thorough survey has been made at Minneapolis-Honeywell of the available literature in the field of helicopter dynamics. From the standpoint of the present study, the obvious question at the beginning was whether there already existed the necessary transient data for the helicopter in the form desired for the present application. In particular, there was the problem of including in the theory the effects of variable RPM of the rotor. It was also desired that a perusal of the literature be made for the purpose of determining which theories, experiments, etc., were likely to be most useful in guiding the present development in the event that new stability equations had to be derived.

Presented in Appendix A is a bibliography, arranged chronologically, of the documentation examined during the initial phases of the present research project. The list does not include reports dealing primarily with vibration or flutter, nor material which was very recently received and, therefore, had little influence on the developments reported here.

The theory for helicopter dynamics has progressed to a relatively advanced state but for the most part remains without experimental corroboration. Regarding the effect of transients in rotor RPM, previous investigators chose to neglect this effect in their evaluation of helicopter dynamics.

2.1.2 Helicopter Autopilot Development

The reports on earlier work in this field are included in the bibliography in Appendix A. Every effort has been made to benefit the present effort by the experiences of prior developments. Here again, however, the scope of these previous projects was of a more limited nature than that planned here.

2.1.3 Helicopter Rotor RPM Control

A bibliography of previous work in this field is presented in Appendix B. A study of these reports has indicated that a need exists for the establishment of basic theoretical criteria for the design of these controls, including a determination of whether some coupling with the helicopter attitude stabilization system is desirable.

2.2 SURVEY TRIP

In Interim Report AD 5143-TR1, Reference (1), are presented the results of a survey trip made to secure up-to-the-minute information on various aspects of helicopter automatic control problems. Quoting from the Abstract of Reference (1),

"Research personnel of the Aeronautical Division have completed a program of visits to a group of facilities concerned with helicopter flight control and helicopter engine control. The purpose of these visits was to learn at first hand whether certain information was available at these facilities which could be utilized in the research study under Contract No. Nonr-929(00)—hereinafter referred to as the subject contract or subject study. The information desired included dynamic and static stability derivatives, steady state and transient engine characteristics, pilot opinions on and desires for helicopter handling and flying qualities, and suggestions as to the analytical methods which should be employed in the subject study. This report is a compilation of the information received during the course of the several visits described herein."

The reader is referred to the above report for further details.

III EQUATIONS OF HELICOPTER MOTION IN HOVERING

Inasmuch as the review described in Section II had indicated that the theoretical equations for helicopter motion had not been previously derived as required for the present study, it was evidently necessary to provide such a development here. This work has been described in three previous Interim Reports, References (2)- (4) . The abstracts from these reports are reproduced below:

A. AD 5143-TR2: "A review is presented of the problem of the induced velocity at the rotor of a nominally-hovering helicopter which is undergoing transient motion. It has been suggested that the variation of induced velocity occurring during the disturbance experienced by the helicopter may have a significant effect on the transient motion of the helicopter. It is noted, however, that it has been almost universal practice to ignore the effects of variations in the induced velocity in studying helicopter dynamics, because of the additional labor that would be required to evaluate and include these effects. It is concluded that the effort under Contract No. Nonr-929(00) must of necessity be similarly limited, but it is suggested that the Office of Naval Research consider this problem as worthy of a separate research project for University research personnel, or the National Advisory Committee for Aeronautics."

B. AD 5143-TR3: "This report contains the development of the theoretical equation for the aerodynamic torque absorbed by a helicopter rotor which is experiencing transient disturbances in RPM while the helicopter is hovering. Inasmuch as the dynamical equation for torque was found to include the effects of the simultaneous transients in blade coning angle and vertical velocity of the aircraft, it was necessary to derive auxiliary equations defining these additional variables, and these equations are also shown here.

The system of equations derived in this report is required in the analytical study of controls for automatic regulation of helicopter rotor RPM."

C. AD 5143-TR7: "This report contains the development of the theoretical equations defining the motions of a helicopter experiencing transient disturbances from steady-state hovering. Included in this treatment of helicopter motion is the consideration of the influence of simultaneous transients in rotor RPM. The helicopter chosen for this study was of the single main rotor type, employing a tail rotor for torque compensation.

On the basis of the linearized analysis, it was established that, while variations in rotor RPM do not couple directly with pitching and rolling motions, by virtue of the action of the tail rotor a secondary type of coupling was found to exist between the aforementioned variables."

While Report -TR7 has included in a more generalized way the material in Report -TR3, the latter report provided the equations on at least an approximate basis for an early attack on the rotor RPM control problem. By thus postponing the consideration of autopilot-RPM coupling requirements, it was possible to gain considerable insight into this problem with a minimum of complication.

The details of this phase of the study effort can be obtained from the aforementioned Interim Reports.

IV DYNAMICS OF HELICOPTER ENGINES

4.1 TURBO-PROP ENGINE (SINGLE-SPOOL)

The representation of the engine transfer function was determined largely from a study of the reports of the NACA dealing with this subject. Of principal importance in this connection were References (5) and (6). The theoretical transient characteristics obtained from this examination as well as the experimental data (taken from Reference 7) used therewith have been presented in Interim Report -TR4 (Reference 8). As it finally was employed in the present analysis, the transfer function for the single-spool turbo prop engine was characterized by two cascaded, first-order time lags; the first was representative of the delay time between fuel valve actuation and energy availability, while the second was related to the inertia characteristics of the rotating system.

4.2 RECIPROCATING ENGINE (SINGLE STAGE SUPERCHARGER)

The study of piston engines requires first that dynamic equations of motion be derived for the purpose of analysis or simulation. The following is a discussion of the assumptions and decisions made in obtaining the resultant relationship between throttle change and rpm change.

Inasmuch as the determination of the piston engine dynamical characteristics (and the simulation thereof) is accomplished in a more amenable fashion by experimental rather than theoretical means, it was desired to survey the availability of such experimental data (Reference 1). According to the engine manufacturers, no data of the type sought were available. It was therefore concluded that two courses of action were open: (1) obtain the engine dynamic equations mathematically, and (2) set up an engine test program and obtain the equations experimentally. Both courses were adopted and results thus far obtained are given below.

Because the interest here in the piston engine concerns the dynamics between throttle input and RPM output, it was quickly determined that at least one lag would exist because of engine inertia. Whether other lags exist was not immediately obvious. The basic problem here was to determine the dynamic relationship between throttle and engine torque, since the lag mentioned above determines the dynamics between engine torque and RPM. Taylor and Taylor, on page 155 of Reference (9), discuss the problem of delay in acceleration after throttle increase. Apparently some of the additional fuel is not immediately vaporized, but rather flows slowly along the manifold walls, delaying the realization of the required torque

associated with the throttle change. Partial compensation for this phenomenon is generally obtained through use of accelerating wells which add additional fuel during accelerations. During deceleration the excess fuel which is flowing along the walls causes temporary delay in reducing engine torque output, while this latter phenomenon is of little concern in most instances, for precise RPM control of a helicopter it would appear that some consideration should be given to this deceleration phenomenon. Consequently, further knowledge on this subject was sought from various authoritative sources (References (10-14) which treat the general subject of engine testing, but no new material was derived.

Several reports on the control of piston engines are based on the assumption that no lag exists between throttle and torque; e.g., in a recent report (see Reference 15) the assumption is made that engine torque responds to throttle motion without lag. On the other hand, other reports give the impression that additional lags are important; e.g., in Reference (16) which discusses automobile engine acceleration tests run for the purpose of determining what additional fuel should be injected during acceleration, a number of curves are presented from which it appears that a lag of $1/(1s + 1)$ should be included in the analysis. Reference (17) which contains a dynamic analysis of a turbo-supercharged engine discusses a lag chosen as $1/(.5s + 1)$, which represents the lag in changing the flow of fuel air mixture, and also a lag representing the time required for the gas to enter the engine and develop the associated torque. The only feasible means of determining whether such lags do indeed exist on the R1820-84 engine (chosen as the vehicle for this study) is by engine acceleration tests. AEL is equipped to run such tests and have scheduled same for early September, 1953. Because an R1820-84 engine is not readily available, an R1820-74 which is available is being substituted. From a dynamics standpoint the two engines are similar. The engine tests will also include the dynamics of the supercharger which must be included in the present analysis. Inertia of main rotor, tail rotor, gear box, etc. will be simulated by appropriate inertia on the engine shaft.

With the above considerations in mind an equation expressing the dynamics of the engine was derived, assuming that the AEL test data would be available at some future date to supplement or modify the present analysis. The development of this equation follows.

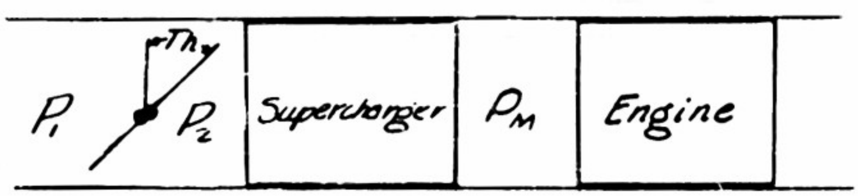

FIGURE 1

The basic equation expressing the acceleration of the rotor and engine system is

$$\Delta Q_e - \frac{\Delta Q_A}{R_1} = I_{TOT.} \Delta \dot{\Omega} \qquad (1)$$

where

ΔQ_e = change in engine torque output
ΔQ_A = change in rotor load torque
$I_{TOT.}$ = total moment of inertia
$\Delta \Omega$ = change in engine RPM
R_1 = engine to rotor gear reduction

The moment of inertia $I_{TOT.}$ is composed of I_R, I_e, and I_c, the moments of inertia of the rotor, the engine, and the compressor, respectively.

Now $$I_{TOT.} = I_e + \frac{I_R}{R_1^2} + \frac{I_c}{R_2^2}$$

where R_1 and R_2 are gear reductions between engine and rotor, and engine and compressor, respectively.

ΔQ_A is determined as a function of those variables having a bearing on the aerodynamic load of the rotor, while ΔQ_e is expressed as a function of manifold pressure change and engine RPM change, as given normally by performance curves. The latter relationship can be written as:

$$\Delta Q_e = \left.\frac{\partial Q_e}{\partial P_M}\right|_{\Omega} \Delta P_M + \left.\frac{\partial Q_e}{\partial \Omega}\right|_{P_M} \Delta \Omega$$

Writing $\left.\frac{\partial Q_e}{\partial P_M}\right|_{\Omega} = A_1$ and $\left.\frac{\partial Q_e}{\partial \Omega}\right|_{P_M} = A_2$ there results

$$\Delta Q_e = A_1 \Delta P_M + A_2 \Delta \Omega \qquad (2)$$

Referring now to Figure 1, the following equations may be written:

$$\Delta P_M = B_1 \Delta P_2 + B_2 \Delta \Omega \qquad (3)$$

where

ΔP_M = change in manifold pressure,
ΔP_2 = change in compressor inlet pressure,
$B_1 = \left.\frac{\partial P_M}{\partial P_2}\right|_{\Omega}$,
and $B_2 = \left.\frac{\partial P_M}{\partial \Omega}\right|_{P_2}$.

$$\Delta P_2 = C_1 \Delta W_a + C_2 \Delta Th \tag{4}$$

where

ΔW_a = change in air mass flow,
ΔTh = change in throttle angle,

$$C_1 = \left.\frac{\partial P_2}{\partial W_a}\right|_{Th},$$

and $$C_2 = \left.\frac{\partial P_2}{\partial Th}\right|_{W_a}.$$

$$\Delta W_a = D_1 \Delta P_M + D_2 \Delta \Omega \tag{5}$$

where

$$D_1 = \left.\frac{\partial W_a}{\partial P_M}\right|_{\Omega},$$

$$D_2 = \left.\frac{\partial W_a}{\partial \Omega}\right|_{P_M}.$$

In equation (5) it is assumed that changes in engine back pressure will be negligible. Other assumptions and approximations involved in equations (3) to (5) inclusive are similar to those of the analysis given in Reference (17).

Combining equations (1) to (5) inclusive results in the simulation equation for the engine. Thus,

$$E_1 \Delta \Omega + E_2 \Delta Th - \Delta Q_A / R_1 = I_{TOT.} \Delta \dot{\Omega}$$

where $$E_1 = A_2 + A_1 B_2 + \frac{A_1 B_1 (C_1 D_1 B_2 + C_1 D_2)}{1 - C_1 D_1 B_1}$$

and $$E_2 = \frac{A_1 B_1 C_2}{1 - B_1 C_1 D_1}$$

Rewriting and including the Laplacian operator results in:

$$\Delta \Omega = \frac{K_1}{\tau s + 1} \Delta Th - \frac{K_2}{\tau s + 1} \Delta Q_A \tag{6}$$

where $$\tau = \frac{I_{TOT.}}{E_1},$$

$$K_1 = E_2 / E_1,$$

and $$K_2 = \frac{1}{R_1 E_1}.$$

The additional lags* relating throttle change to engine torque change as developed in Reference (17) may be incorporated resulting in:

$$\Delta\Omega = \frac{K_1}{(\tau_1 s+1)(\tau s+1)(\tau_2 s+1)}\Delta Th - \frac{K_2}{\tau s+1}\Delta Q_A \qquad (7)$$

It is expected that the AEL tests will demonstrate that τ_1 and τ_2 will vary with operating condition and will also have different values for acceleration and deceleration. These variations will be taken into account in the simulation as the data become available.

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* τ_2 represents the time required for the change in fuel-air flow to enter the engine, be compressed, ignited and expelled, and is taken in Reference (17) to be 0.0444 sec. τ_1 represents the lag in changing the quantity of fuel-air mixture and is taken to be 0.5 sec. after Reference (17).

V CONTROL OF ROTOR RPM IN HOVERING (TURBO-PROP ENGINE)

5.1 ROOT LOCUS STUDY

On the basis of the approximate relationships for helicopter motion in Reference (3) and the engine transient characteristics in Reference (8), an analytical study of rotor RPM automatic control (presuming no coupling with or from the attitude control system) was undertaken. This has been described in Interim Report AD 5143-TR5 (Reference 18), wherein the Abstract stated, "This report presents the results of a preliminary analytical study of the RPM and temperature control of a helicopter turboprop engine and rotor combination. The system considered is spoken of as being one in which RPM is controlled by the manipulated variable fuel flow, and temperature is controlled by the manipulated variable collective pitch. The following three simple configurations were investigated using root locus procedures:

1) Integral control in the RPM feedback loop and proportional control in the temperature feedback loop.

2) Proportional control in the RPM feedback loop and integral control in the temperature feedback loop.

3) Integral control in the RPM feedback loop and rate control in the temperature feedback loop.

The conclusion reached is that the third configuration listed holds the greatest promise of satisfactory dynamic response of RPM." For further particulars the Interim Report should be consulted.

5.2 REAC STUDY

The use of the analog computer* greatly facilitates the study when it is desired to explore the performance of a great variety of configurations of closed-loop control systems. This approach was employed in the present research program, as described in Interim Report AD 5143-TR4 (Reference 8). The Abstract in that document stated, "This report contains a presentation of the results of an analog (REAC) computer study of the automatic control of rotor RPM of a single-spool

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* See also Section VI-B on the question of computer accuracy.

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turbo-prop engine. The equations involved in the REAC simulation are included, as well as extended discussion of the simulation and associated research. Results presented include actual REAC runs, and a tabulation showing a comparison of manual control of rotor RPM with the performance of various automatic controls governing rotor RPM. The study also includes consideration of the influence of various automatic RPM control configurations on vertical maneuverability of the helicopter."

One of the special features of this phase of the study was the development of the device "Steady Eddie" for use in conjunction with the REAC. By means of this equipment it was possible to pursue several by-product inquiries of importance to the subject of automatic control of rotor RPM, including the one stated at the end of the above Abstract. The description of "Steady-Eddie" is presented in Interim Report AD 5143-TR6 (Reference 19).

VI WORK IN PROGRESS

6.1 EQUATIONS OF MOTION IN FORWARD FLIGHT

While the hovering regime represents an important mode for automatic controls operation, especially for ASW-type of duty, it is clearly evident that the criteria for design must also be based on requirements imposed by the forward flight regime. To provide the necessary helicopter transfer functions for controls analyses, an effort is underway to develop the equations of motion in forward flight with rotor RPM degree of freedom.

To date the above development has progressed to the point of the derivation of the transients in blade coning and in tip path plane inclination, where the helicopter C.G. is constrained to motions in the longitudinal plane only. Reproducing this work in detail here does not appear to be warranted, but it is of interest to report the fact that rotor RPM variations proved to be coupling factors in the blade motion equations, along with transients in helicopter C.G. movement. The effect of the coupling has as yet not been determined.

6.2 COMPLETE CLOSED-LOOP CONTROL STUDY

In the initial helicopter control study which will consider the hovering regime of flight, there will be five controlled variables:

1. Ω = Speed of the engine (and thus speed of both the main and tail rotor since both are geared to the engine with a given, fixed gear ratio.
2. α_y = Longitudinal pitch of the helicopter about the y axis.
3. α_x = Roll angle of the helicopter about the x axis.
4. α_z = Heading angle or yaw of the helicopter about the z axis.
5. z = Helicopter altitude or movement in the z direction.

The objective will be to study the responses obtained by various control configurations by REAC and analytical means, and to determine the dynamical characteristics from the absolute

stability, transient and steady-state performance standpoints. Since the purpose will be to determine and compare the performance of various practical methods of control, and to make specific recommendations from these findings, no minimum design criteria as to speed of response, steady-state error, maximum overshoot or frequency of oscillation need be established at the outset. The simplest and most economical control configuration that results in minimum steady-state errors, and further, that allows the transient deviation to be a minimum both in time duration and amplitude will be judged best.

If the components in the control loop are taken in the order of the information flow the five controlled variables must first be measured. It is these measured quantities that are controlled. Therefore, there should be minimum lags in the sensing units, since it is desirable that their outputs be as representative of the actual physical inputs as possible.

Speed Control: If it is desired to regulate speed using proportional and integral control alone, the Woodward Governor is a compact instrument that combines both the measuring and regulating functions in one component. The transfer function for this unit is usually represented by the integral and proportional operations plus a single order lag with a time constant of about 0.05 sec.

In some applications it is desirable to have controls such as proportional, integral, and/or rate operate on the speed error in the forward loop. Then a D.C. tachometer (which needs a filter) performs the speed-sensing function, and a D.C. network utilizes its output to secure the control configuration.

If output speed control is desired, components such as accelerometers, A.C. tachometers and/or integral devices can be placed in the feedback path. It is also common practice to use a combination of speed error and output speed control, and the desirability of each method depends upon the plant transfer function, and the point of application of the load disturbances.

Roll and Pitch Control: It is conventional to sense roll and pitch displacement with one vertical gyro. This has negligible dynamics, since its rotor is fixed in space, and the displacement function may be considered instantaneous.

The customary method of securing rate is by the use of rate gyros—one for each axis controlled. The single-degree-of freedom, viscous-damped rate gyros are thought unnecessarily accurate and costly for helicopter applications. Their threshold is needlessly low—0.003 deg/sec to 0.0006 deg/sec -- and they require extra equipment such as amplifiers, etc. Damped rate gyros are under development that have a variable frequency and damping ratio range. These will be simulated on the REAC and the characteristics of the gyro simulation varied to secure optimum response.

It is planned that consideration will also be given to controlling pitch and roll disturbances by means other than the use of the position gyro in the fuselage. Nothing concrete has been established yet in this regard.

Heading Control: Although complete information on the study helicopter has not as yet been received, it is most probable that the helicopter will be completely instrumented and therefore be equipped with a Gyro Magnetic Compass. In this unit a magnetic compass aligns a position gyro to magnetic north and puts out a synchro signal. It is only necessary then to supply a compass coupler, which is essentially a follow-up motor that drives a potentiometer in response to the synchro signal. The important dynamics of this system are in the compass coupler, and a representative simulation would be a second order system with a natural frequency of about 3.2 CPS at a damping ratio of about 0.7. If yaw rate is desired a rate gyro or network must be used.

Altitude Control: The present preliminary thinking on altitude sensing is along the lines of using a radio altimeter or the sonar cable. Except for cable dynamic lags due to wind loads in the latter, both means of sensing can be thought of as being instantaneous. Pressure sensing altitude controllers might cause trouble because of the difficulty in securing an accurate static pressure source due to the rotor downwash.

Regulation: The first plan is to perform the regulating functions in the following ways:

1) Engine speed is to be regulated by a servo motor attached to the throttle lever or carburetor butterfly valve governing throttle position (Th).

2) Longitudinal pitch will be regulated by a servo motor to cyclic pitch (θ_y).

3) Helicopter roll will be regulated by a servo motor to cyclic pitch (θ_x).

4) Heading will be regulated by a servo motor attached to the lever controlling tail rotor blade pitch (θ_t).

5) Altitude will be controlled by a servo motor regulating main rotor collective pitch (θ_0).

The underlined quantities in the above are, therefore, the manipulated variables.

When both engine speed and helicopter altitude are subject to automatic control, it is presently felt to be more

desirable to control engine speed with throttle and altitude with collective pitch (as above), than the alternate method of controlling engine speed with collective pitch and altitude with throttle . Collective pitch is usually thought of as a primary control (power required) while engine speed is controlled by the throttle setting (power available) that is dictated by the load requirements of the rotor. (See also Reference (15) for further discussion.)

During the course of the controls analyses, consideration will also be given to cross-coupling in the feedback paths.

The most recent trend in helicopter autopilots is toward the differential system , thus eliminating the formation stick that is permissable in the conventional airplane. In the differential system the pilot controls do not move when the autopilot is operating, and when on autopilot, the helicopter can be controlled from the cockpit in the normal manner. Since the S-58+ is thought to have a hydraulic boost control, a differential hydraulic servo will be considered first in the control simulation. Test results show that even for small changes in maximum amplitude the frequency response varies widely, and the unit is therefore quite different from a simple linear system. Further, the amplifier used has a marked effect on the servo response. Because of these complications, for simulation purposes, a simple first-order lag of 5 cps at 45 degrees will be taken to represent the servo units. This specification is far beyond the frequency of any helicopter motor that will be encountered.

<u>Functional Dependency</u>: The most direct way of stating the functional dependency between the variables is to list the effects of a change in the manipulated variables on the dependent variables before the control corrections take place. This is done in the following paragraphs for each controlled variable.

I. Engine speed (Ω) as a controlled variable. $+\Delta Th$ (throttle) will affect the following:

1. speed of the main and tail rotor.
2. α_z (yaw) since tail rotor thrust will increase.
3. z (altitude) since main rotor thrust will increase.
* 4. y (side displacement) since tail rotor thrust will increase.
* 5. α_x (roll) since tail rotor thrust will increase.

+ See Section VII for further reference to the S-58 helicopter (also referred to as the XHSS-1).

II. Longitudinal Pitch (α_y) as a controlled variable. $+\Delta\theta_y$ will affect the following:

1. x (forward displacement) since main rotor thrust is inclined.
2. α_y (pitch) since a pitching moment is produced by the main rotor thrust component.
3. * α_x (roll) because of coupling in main rotor.

III. Roll angle (α_x) as a controlled variable. $+\Delta\theta_x$ will affect the following:

1. y (side displacement) since main rotor thrust is inclined.
2. α_x (roll) since a rolling moment is produced by the main rotor thrust component.
3. * α_y (pitch) because of coupling in main rotor.

IV. Yaw Angle (α_z) as a controlled variable. $+\Delta\theta_t$ will affect the following:

1. α_z (yaw) since tail rotor thrust will increase.
2. * y (side displacement) since tail rotor thrust will increase.
3. z (altitude) since load on engine is increased.
4. * Ω (engine speed) since load on engine is increased.
5. * α_x (roll) since tail rotor thrust causes rolling moment.

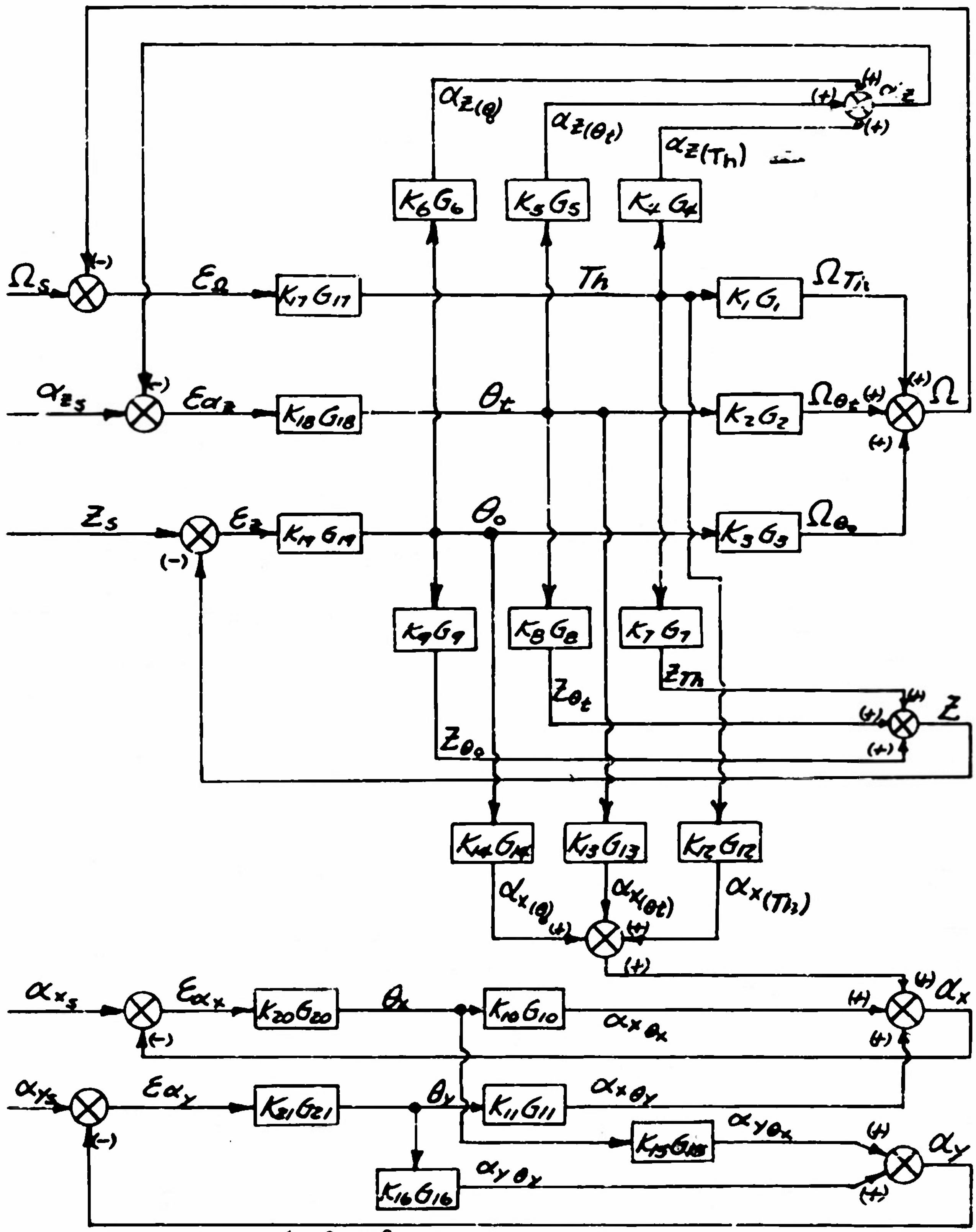
V. Altitude (z) as a controlled variable. $+\Delta\theta$ will affect the following:

1. z (altitude) since thrust of main rotor increases.
2. Ω (engine speed) since load on main rotor increases.
3. α_z (yaw) since engine speed changes and thus also tail rotor thrust.
4. * y (side displacement) since tail rotor thrust changes.
5. * α_x (roll) since tail rotor thrust changes.

The effect of the independent variables on those dependent variables marked (*) are small and possibly negligible at least for analytical calculations.

The above dependency can be summarized to produce the more convenient block diagram shown in Figure 2. This gives an overall picture of the problem in its most complete form, and is substantially the system that will be placed on the REAC.

FIGURE 2. Block Diagram of Proposed Control Problem



There are 10 equations of dynamics involved (the six degrees of freedom of a body in space, three rotor flapping equations and an engine equation), and as the block diagram shows, for analytical work these 10 must be solved 16 times to produce the indicated transfer functions. $K_{17}G_{17}$, $K_{18}G_{18}$, $K_{19}G_{19}$, $K_{20}G_{20}$, and $K_{21}G_{21}$ are the 5 control blocks and symbolically are thought of as containing the transfer functions of the sensing, regulating and control units.

Every effort will be made to simplify the analytical treatment wherever engineering judgment indicates such simplification to be feasible.

Use of the Analog Computer: There has recently been some discussion in regard to the possible inadequacy of the REAC as a means of simulating a helicopter control problem. (See for example, Reference 21.) The point raised seems to be that because of the widely different frequencies of the helicopter motion and rotor motion, difficulty will be encountered in that the analog computer dynamics will obscure the high speed rotor dynamics; and that if the time scale is adjusted to avoid this difficulty, computer drift and long solution times are limiting factors. It is the purpose in what follows to indicate that in all probability computer dynamics do not affect the helicopter simulation, and thus the time scale need not be changed.

It is recognized here that the electronic differential analyzers utilize elements that unavoidably introduce errors in the simulation. Reference (22) states that in certain extreme cases an error of 1 percent can be produced by an adding unit having a bandwidth two thousand times the highest frequency present in the simulation. This order of magnitude is within the accuracy of any helicopter characteristics used in the simulation. Reference (22) also states that these errors are most important for simulations having characteristic roots lying near the imaginary axis.

A simulation of the stabilized helicopter with rotor dynamics included, results in roots of the following general classes:

1. Low frequency poles (less than 2 rad/sec) and of damping greater than 0.6.
2. Moderately high frequency, moderately damped blade-motion poles.
3. A high frequency (35 rad/sec), low damped (DR = .2) blade-flapping-motion complex pair, together with a set of complex zeros in the same position on the right hand plane.

The most difficult task for the computer then is the simulation of the high frequency pair near the imaginary axis.

As is well known, high frequency poles have a negligible effect on the shape of a response determined by low frequency roots. However, they do have a marked effect on the response magnitude. In the helicopter simulation the complex zeros in the right hand plane nullify even the effect the high frequency complex pair would have on the gain if they existed alone. It therefore seems logical to conclude that the simulation errors (if they exist) are unimportant, since the error-sensitive, high-frequency poles themselves are unimportant.

It is important to realize that the above statement should not be interpreted to mean that the rotor dynamics themselves can be disregarded. It is suggested that only the high frequency, low damped pole-zero pairs that make up a portion of the response can be neglected. If any appreciable errors occur in the REAC simulation, the major portion is in these unimportant roots.

In order to further substantiate the validity of the REAC simulation the following simple test was conducted on the REAC:

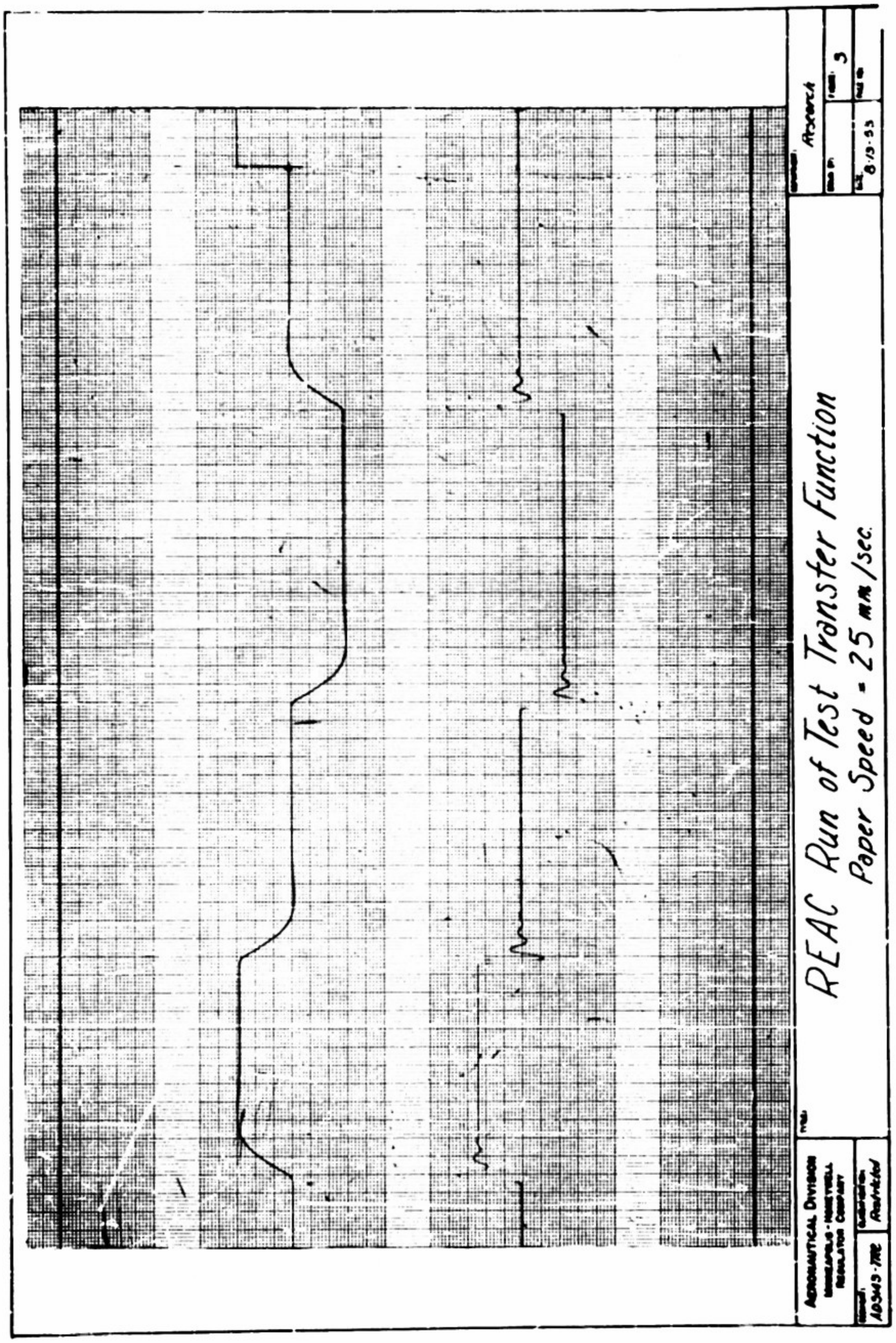
1. A step function input was introduced into the transfer function.

$$\frac{A}{\left[s^2+(2)(.7)(6)s+36\right]\cdot\left[s^2+(2)(.209)(33.55)s+(33.55)^2\right]}$$

   This contains a pair of high frequency low damped poles simulating two of the blade motion roots, and a low frequency, moderately damped complex pair simulating the helicopter motion. The result was recorded at a paper speed of 25 mm/sec, and reproduced in Figure 3.

2. The time scale of the above simulation was then reduced by a factor of ten (thus reducing the frequencies by a factor of ten), and the response to a step function recorded at a paper speed of 2.5 mm/sec. This is reproduced in Figure 4.

It is immediately apparent from a comparison of the two figures that they are identical. It seems logical to assume that if any simulation errors existed in Figure 3, they would be reduced by a factor of 10 in Figure 4. The automatic amplifier balance feature of the REAC seems to stabilize the results even at the low paper speed.


REAC Run of Test Transfer Function
Paper Speed = 25 mm/sec.
Aeronautical Division
Minneapolis-Honeywell Regulator Company
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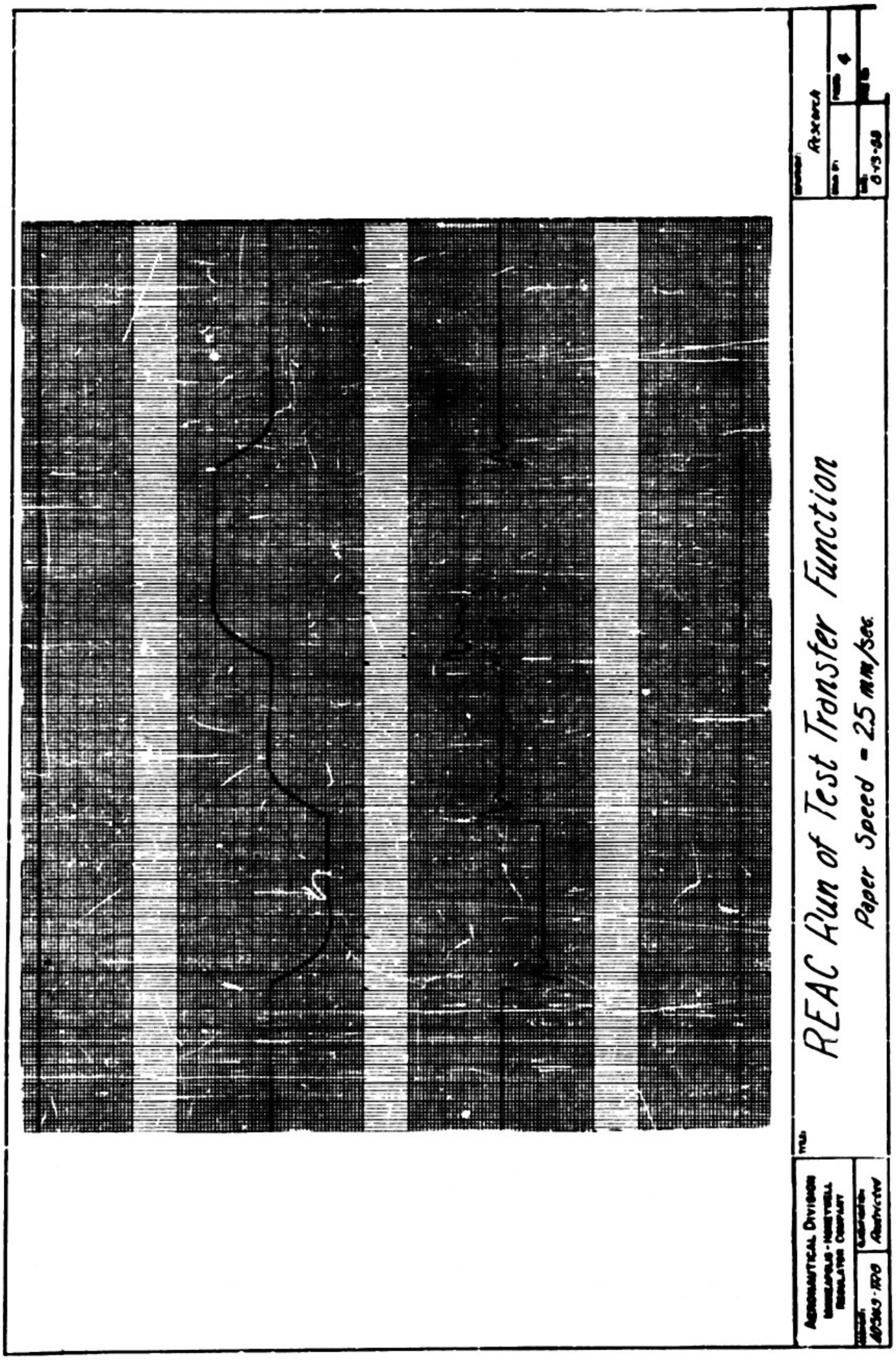
REAC Run of Test Transfer Function
Paper Speed = 25 mm/sec.
Aeronautical Division
Minneapolis-Honeywell
Regulator Company
Restricted

The analytical solution of the response for the magnitude of step input chosen is

$$y = 2.47 - e^{-4.2t}(2.52 \sin 4.29t + 2.42 \cos 4.29t)$$
$$+ e^{-7t}(.0314 \sin 32.8t$$
$$+ .0788 \cos 32.8t)$$

It can be seen from a comparison of the coefficients of sin and cos terms why the high frequency motion does not affect the total response shape. The time to first reach the final value calculated from the low frequency poles is 0.52 sec. This checks both Figure 3 and Figure 4. The percent overshoot determined from calculations on the low frequency poles is 4.6 percent which is, within the degree of reading accuracy, what Figure 3 and Figure 4 indicate.

VII PROPOSED PHASE II PROGRAM

In Phase II of this research project, as has been indicated in previous sections, the effort will be directed toward the development of design criteria for automatic controls of ASW-type helicopters, as exemplified by the XHSS-1. The program has been outlined in some detail in Reference (20), and it essentially tends to limit the scope of activity in a manner which is most apt to produce tangible results for the type of helicopter configuration indicated above.

Initial concern under the continuation program will be with the following:

A. Determination of the analytical processes to be employed in the automatic control system investigation which can proceed with the receipt of various data on the XHSS-1 helicopter;

B. Completion of the development of the forward flight equations of motion;

C. Analysis of the data secured by AEL on reciprocating engine transient behavior.

VIII SUMMARY

In Phase I of the study of automatic control systems for helicopters, the principal accomplishments were related to laying the foundations for servo analysis. These foundations include (a) the development of the equations of motion for hovering and for forward-flight, (b) the development of the equations for the transient characteristics of turbo-prop and reciprocating engines, and (c) the determination of the dynamics of various elements of the closed-loop systems to be analyzed. While some work remains to be done in connection with the above, it will be possible to undertake the controls study with the receipt of the numerical data on the XHSS-1 helicopter which has been chosen as the research vehicle for the present project.

The study of the automatic control of rotor RPM for the case of the turbo-prop engine has been partially completed. It was found that from the standpoint of minimum complexity the use of a control involving only proportional and integral feedbacks would be advisable; but to gain maximum tightness of control, rate feedback should be added.

In Phase II of this research program, the principal effort will consist in the main of servo analyses aimed at determination of the control system design criteria for the ASW-type helicopter. Additional study will also be given to the development of the forward flight equations motion with RPM degree of freedom and to other basic material needed for extension of the controls analyses to include all of the primary modes of helicopter operation.

IX REFERENCES

(1) Warsett, P. & Brown, C.A.: "Summary of Survey Trip Initial Phase", M-H Technical Report AD 5143-TR1, 26 August 1952.

(2) Warsett, P.: "The Problem of the Induced Velocity at the Rotor of a Hovering Helicopter during Transient Motion", M-H Aero Technical Report AD 5143-TR2, 12 November 1952.

(3) Warsett, P.: "Study of Automatic Control Systems for Helicopters, Part I: Aerodynamic Torque of a Helicopter Rotor Experiencing Transients in RPM While Hovering", M-H Aero Technical Report AD 5143-TR3, 10 June 1953.

(4) Warsett, P.: "Study of Automatic Control Systems for Helicopters, Part IV: Equations of Motion for a Nominally-Hovering Helicopter with Rotor RPM Degree of Freedom", M-H Aero Technical Report AD 5143-TR7, 19 June 1953.

(5) Taylor III, B.L. & Oppenheimer, F.L.: "Investigation of Frequency-Response Characteristics of Engine Speed for a Typical Turbine-Propeller Engine", NACA T.R. 1017. 24 March 1950.

(6) Ketchum, J.R. & Craig, R.T.: "Simulation of Linearized Dynamics of Gas-Turbine Engines", NACA T.N. 2826. November 1952.

(7) "Model Specification Continental-Turbomeca Shaft Turbine Model Artouste I", Continental Aviation and Engineering Model Spec. No. 2079, 18 February 1949.

(8) Brown, C.A.: "Study of Automatic Control Systems for Helicopters, Part II: REAC Study of RPM Control for the Single Spool Turbo-Prop Engine", M-H Aero Technical Report AD 5143-TR4, 31 July 1953.

(9) Taylor, C.F. & Taylor, E.S.: "The Internal Combustion Engine", International Textbook Co., Scranton 1948.

(10) Gruber, F.M.: "Automotive Engine Testing", Pitman Publishing Company, 1950.

(11) Young, S.J. & Pryer, R.W.J.: "The Testing of Internal Combustion Engine", Hodder & Stoughton Lmtd., London, 1936.

(12) Judge, A.W.: "The Testing of High Speed Internal Combustion Engines", D. Van Nostrand Company, New York, 1925.

(13) Judge, A.W.: "Automobile and Aircraft Engines", Sir Isaac Pitman & Sons, Ltd., 1937.

(14) Pye, D.R.: "The Internal Combustion Engine", Oxford at the Clarendon Press 1934, pp. 239-244.

(15) Burkam, J.: "Selection of Governor System for HUP Helicopter", Piasecki Helicopter Corporation Report R-36, 27 February 1953.

(16) Eisinger, J.O.: "Engine Acceleration Tests", Trans. SAE, Vol. 22, Part 2, 1927.

(17) Clemens, J.E. etal: "Automatic Control of Aircraft Engines with Turbo Supercharger, AMC, OAR Technical Report No. 2, 1 November 1950.

(18) Albachten, H.: "Study of Automatic Control Systems for Helicopters, Part III: Analytical Study of RPM Control for the Single Spool Turboprop Engine", M-H Aero Technical Report AD 5143-TR5, 23 April 1953.

(19) Gustafson, H.: "Report on an Operational Aid Used in a Simulation Study of Helicopter Control Systems", M-H Aero Technical Report AD 5143-TR6, 1 July 1953.

(20) "Technical Exhibit Proposal for the Continuation of a Study of Helicopter Control System Requirements", M-H Aero Document R-ED411, 20 May 1953.

(21) Ellis, C.W.: "Effects of Articulated Rotor Dynamics on Helicopter Automatic Control System Requirements", Aeronautical Engineering Review, p. 30, July 1953.

(22) Macnee, A.B.: "Some Limitations on the Accuracy of Electronic Differential Analyzers", Proceedings of the IRE, p. 303, March 1952.

X. APPENDIX

A. BIBLIOGRAPHY OF HELICOPTER DYNAMICS*

- Prior to 1940 -

1. Chatley, H.: The Stability of Flying Machines; Principle of the Helicopter. Engineering, London, v. 90, pp. 37-38. 1 July 1910.

2. Bateman, H.: Stability of the Parachute and Helicopter. NACA TR 80. 1920.

3. von Karman, Theodore: Helicopter Theory. Aircraft Engineering, v. 12, no. 139, pp. 271-276. Written: 1921.

4. von Karl Balaban: Zur Stabilitatsfrage des Hubschraubers. Z. F. M. Berlin, v. 13, no. 15, p. 223. August 1922.

5. Crocco, G. Arturo: Inherent Stability of Helicopters. NACA TM 234. 1923.

6. di Flamino Piana-Canova: Verso la stabilizzazione dell'elicottero. L'Ala d'Italia, Milano, v. 3, no. 11, pp. 261-262. November 1924.

7. Florine, N.: Stabilite d'un Helicoptre. Bull. Service Techn. d'Aeronautique. 1930.

8. McClarren, Ralph H.: Development in Stability and Rotor Starting Characteristics of the Autogiro. Aviation Engineering, East Stroudsburg, Pa., v. 4, no. 3, pp. 20-22. April 1931.

9. von Lansdowne, L.: Metal Rotors of Autogiro Hinged for Stability. Iron Age, New York, v. 128, pp. 302-303. July 1931.

10. di Ugo de Caria: La Stabilita degli eilcotteri. L'Aeronautica, Milano, v. 45, no. 7, pp. 471-476. July 1931.

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* Most of the early documents listed are chiefly of historical interest only. Material which was concerned principally with blade motion, vibration, flutter, etc., has been omitted. It is also recognized that there are in all likelihood many interesting and pertinent documents that are not included in this listing because they were not made available to the present research project.

11. Glauert, H.: Some Notes on the Stability and Control of Gyroplanes. British R.A.E. Report B.A. 1016 (Unpublished). March 1933.

12. Lame, M. L. V.: Le Vol Vertical. Blondel et La Rougery, Paris. 1934 (or 1935).

13. Wheatley, J. B.: Control-Force Measurements in Flight of the Pitcairn YG-2 Autogiro. NACA MR, Army Air Corps. 26 February 1936.

14. Wheatley, J. B.: Control-Force and General Performance Tests of Kellett YG-1 Autogiro. NACA MR, Army Air Corps. 27 March 1936.

15. Kussner, H. G.: Helicopter Problems. NACA TM 827. 1937.

16. Focke, H.: Autogiro and Helicopter Problems. Schriften der Deutsch. Akad. der Luftfahrtforschung. v. 22, British R. T. P. Translation 2128. November 1937.

17. Schrenck, M.: Static Longitudinal Stability and Longitudinal Control of Autogiro Rotors. NACA TM 879. 1938.

18. Platt, H. H.: Development of the Helicopter. Institute of Aeronautical Science, Philadelphia Meeting. October 1938.

19. Hohenemser, K.: Dynamic Stability of a Helicopter with Hinged Rotor Blades, Written: December 1938. NACA TM 907.

20. Young, A. M.: A New Parameter of Lifting Rotors. Institute of Aeronautical Science, Philadelphia Meeting. November 1939.

21. Klemin, A., Haugen, V. R., Sherwin, S. B.: Autogiro Rotor Longitudinal Stability. Institute of Aeronautical Science, Philadelphia Meeting. November 1939.

22. Hufton, P., Woodward, A., Bigg, F., and Beavan, J.: General Investigation into the Characteristics of the C.30 Autogiro. British A. R. C. R and M 1859. March 1939.

23. Beavan, J. A.: Note on the Lateral Stability of the C.30 Autogiro Seaplane. British A. R. C. R and M 1970. 3 April 1939.

24. von Schlippe, V. B., and Dietrich, R.: Fur Stabilitat der Hubschrauber. Booklet 16 - The German Academy of Aeronautical Research. 15 July 1939.

25. Dykes, John Christopher: Stability Derivatives of Helicopter Rotors. California Institute of Technology. 1938.

26. Isacco, Vittorio: Modern Helicopter Theory, Part I. Aircraft Engineering, p. 274-283. October 1936.

27. Isacco, Vittorio: Modern Helicopter Theory, Part II. Aircraft Engineering, pp. 303-308. November 1936.

28. Squire, H. B.: Notes on the Stability and Control of a Twin Screw Helicopter. British R. A. E. Report B. A. 1470. April 1938. Restricted.

- 1940 - 1946 -

1. Miehl, M. L.: The Aerodynamics of the Lifting Airscrew with Hinged Blades in Curvilinear Motion. British R. T. P. Translation No. 1533. 1940.

2. Hohenemser, K.: Stability in Hovering of the Helicopter with Central Rotor Location. Written: May 1944. A. M. C. Translation No. F-TS-687-RE.

3. Hohenemser, K.: Longitudinal Stability of the Helicopter in Forward Flight. Written: July 1944. A. M. C. Translation No. F-TS-688-RE.

4. Hohenemser, K.: The Theory for the Control of the Blade Angle of the Helicopter. Written: July 1944. A. M. C. Translation No. F-TS-1004-RE.

5. Nikolsky, A. A.: Helicopter Design Theory. Princeton University Press, 1944.

6. Donovan, A. F., Goland, M.: The Response of Helicopters with Articulated Rotors to Cyclic Blade Pitch Control. Journal of Aeronautical Sciences, p. 387. October 1944.

7. Sissingh, G.: Contributions to the Dynamic Stability of Rotary-Wing Aircraft with Articulated Blades. Part I General Principles. Written: September 1944. A. M. C. Translation No. F-TS-690-RE.

8. Hohenemser, K.: Lateral Stability of the Helicopter in Steady Forward Flight. Written: October 1944. A. M. C. Translation No. F-TS-691-RE.

9. Hohenemser, K.: The Pull-Up of the Helicopter. Written: December 1944. A. M. C. Translation No. F-TS-692-RE.

10. Kelley, B.: Helicopter Stability with Young's Lifting Rotor. Written: March 1945. S. A. E. Journal. December 1945.

11. Dorand, M.: Control, in Hovering, of Large Helicopters with a Single Rotor or with Coaxial Rotors. Congres National De L'Aviation Francaise. 1945.

12. Sissingh, G.: Contributions to the Problem of the Dynamical Stability of Rotary Wing Aircraft with Articulated Blades, Part IV. Translation by Ministry of Aircraft Production, Voelkenrode, No. CDC/114-T. 1946.

13. Sissingh, G.: The Dynamic Stability of Helicopters with Articulated Rotors. Second Partial Report. A. M. C. Translation No. F-TS-1002-RE. 1946.

14. Stewart, W.: General Handling Tests of the Sikorsky R-4B Helicopter (Hoverfly Mk 1). British A. R. C. R and M 2431. October 1946.

15. Hohenemser, K.: Theory of Helicopter Control in Hovering Flight. A.M.C. Translation No. F-TS-1006-RE. 1946.

16. Ritti, Edward, and Landis: Test Data and Performance Curves for Pitching and Flapping Characteristics of KH-1X Synchropter Model. Kellett Autogiro Corporation, Report 1430.3. February 1942.

17. Kemp, B. L.: Aerodynamic Characteristics of the 1/10 Scale Models of the XR-4 and YR-4A Helicopter Fuselages. Written: 21 January 1943. United Aircraft Corporation, Report No. W. T. T. 191.

18. Kemp, B. L.: Aerodynamic Characteristics of the 1/12 Scale Model of the XR-6 Helicopter Fuselage. Written: 23 April 1943. United Aircraft Corporation, Report No. W. T. T. 197.

19. Strom, G. H.: Wind Tunnel Tests of Kellett XR-Fuselage. Kellett Report No. 1430.7. May 1944.

20. Sissingh, G.: Stability of Lifting Rotors. Written: October 1944. A. M. C. Translation No. 19599.

21. Wiesner, W.: An Analysis of the Controls and Maneuverability of the XR-8 Helicopter. Kellett Report No. 1430.11. January 1945.

22. Wiesner, W.: Calculated Directional Stability Characteristics of the XR-10 Helicopter. Kellett Report No. 1430.9. 12 January 1945.

23. Sissingh, G.: Contributions to the Problem of Dynamical Stability of Rotary Wing Aircraft with Articulated Blades (Part III). M. A. P. Volkenrode Reports and Translation No. 98. 15 June 1946.

24. Gail, A: Investigation of the Control Delay of the IHJD-1 Helicopter in Hovering Flight. McDonnell Aircraft Corporation, Report No. H1-117-6. 2 October 1946. Restricted.

- 1947 -

1. Bennett, J. A. J.: Limitations in Helicopter Design. Proceedings of Third Annual Forum, American Helicopter Society, Philadelphia, Pa. March 1947.

2. Bruel, A.: Practical Stability and Controllability of Rotary-Wing Aircraft While Hovering. Third National Congress of French Aviation, Cornell Translation. April 1947.

3. Dingeldein, R. C., and Schaefer, R. F.: Full-Scale Investigation of the Aerodynamic Characteristics of a Typical Single-Rotor Helicopter in Forward Flight. Written: February 1947. NACA TN 1289.

4. Mashman, J.: How to Fly the Bell Model 47-B. American Helicopter, p. 12. May 1947.

5. Seibel, C. M.: Stability and Control Characteristics of a Simplified Helicopter. S.A.E. National Personal Aircraft Meeting. May 1947.

6. Bennett, J. A. J.: Limitations in Helicopter Design. American Helicopter, p. 10. June 1947.

7. Young, A. M.: The Helicopter and Stability. Inter Avia. June and July 1947.

8. Langewiesche, Wolfgang: Notes from Helicopter School, Parts I-IV. Air Facts Magazine. June-September 1947.

9. Hafner, R.: Rotor Systems and Control Problems in the Helicopter. Anglo-American Aeronautical Conference, London. September 1947.

10. Just, W.: Calculating the Longitudinal Stability and Control of Helicopters. Inter Avia, p. 31. December 1947.

11. McDonald, Meyers, Sloan, and others: Control and Trim Problems of the XH-16 Helicopter. Piasecki Helicopter Corporation, Report No. 15-A-03A. 1 October 1947. Restricted.

12. Prieto, A. G.: Static Stability of a Rigid Rotor Synchropter: Part I: Longitudinal Stability in Level Flight; Part II: Rolling Stability in Hovering in a Lateral Gust. Kellett Aircraft Corporation, Report 1430.20. February 1947.

13. Stewart, W.: Interim Note on the Dynamic Longitudinal Stability of a Single-Rotor Helicopter. R.A.E. Technical Note No. Aero 1885. April 1947.

14. Fail and Squire: 24 Foot Wind Tunnel Tests on Model Multi-Rotor Helicopter, Part II - Tandem Twin-Rotor Helicopter. British R. A. E. Report No. Aero. 2207. June 1947. Confidential

- 1948 -

1. Miller, R. H.: Helicopter Control and Stability in Hovering Flight. Written: 19 January 1948. Journ. Aero. Sci., p. 453. August 1948.

2. Montgomery, Giles N.: Unique Rotor Affords New Safety. Aviation Week, p. 28. 26 January 1948.

3. Stewart, W.: Flight Testing of Helicopters. Written: 29 January 1948. Journ. Royal Aero. Soc1, p. 261. May 1948.

4. Crane, L.: Importance of Dynamic Stability. American Helicopter Magazine, p. 17. February 1948.

5. Gustafson, F. B., and Reeder, J. P.: Helicopter Stability. NACA RM L7K04. 12 April 1948.

6. Meyers, G. C.: Gyroscopic Forces on Hinged Rotors. Fourth Annual Forum, American Helicopter Society, Proceedings of. 22 April 1948.

7. Hohenemser, K.: Contribution to the Problem of Helicopter Stability. Fourth Annual Forum of American Helicopter Society, Proceedings of. 22 April 1948.

8. Reeder, J. P., and Gustafson, F. B.: Notes on the Flying Qualities of Helicopters. Fourth Annual Forum, American Helicopter Society, Proceedings of. 22 April 1948.

9. Dorand, R.: Helicopters Stabilizing Device. Fourth Annual Forum, American Helicopter Society, Proceedings of. 23 April 1948.

10. Nikolsky, A. A., and Seckel, Edward: An Analysis of the Transition of a Helicopter from Hovering to Steady Autorotative Vertical Descent. Written: May 1948. NACA TN 1907.

11. Gessow, Alfred: Standard Symbols for Helicopters. NACA TN 1604. June 1948.

12. Gessow, Alfred: Bibliography of NACA Papers on Rotating-Wing Aircraft. NACA RM L7J30. July 1948.

13. Sissingh, G.: Investigations on Automatic Stabilization of the Helicopter. Part I (Hovering Flight). British R.A.E. Report Aero 2277. July 1948.

14. Burkam, J. E.: Stability Experiments with Models. American Helicopter, p. 8. July 1948.

15. Erickson, F.: U.S. Coast Guard Helicopter Stabilizer. American Helicopter Magazine, p. 14. August 1948.

16. Stuart III, J.: The Helicopter Control Rotor. Rotating Wing Aircraft Session, 16th Annual Meeting, I.A.S., New York, January 26-29, 1948. I.A.S. Fairchild Preprint Number 110.

17. Miller, R. H.: Some Aspects of the Helicopter Stability and Control Problem. Proceedings VII Congress of Applied Mechanics, p. 569. September 1948.

18. Sissingh, G. J.: Automatic Stabilization of Helicopters. Journ. Hel. Assoc. of G.B., v. 2, no. 3. 23 October 1948.

19. Reeder, J. P., and Gustafson, F. B.: On the Flying Qualities of Helicopters. Written: 10 November 1948. NACA TN 1799.

20. O'Dea, John: A Proposed Method of Determining the Frequency Response of a Helicopter by Analysis of Recorded Transients. Cornell Aero Lab Flight Research Department Report No. TG-587-F-1. 24 November 1948.

21. Zbrozek, J.: An Investigation of the Lateral and Directional Behaviour of a Single Rotor Helicopter (Hoverfly Mk. I). British R.A.E. Report No. Aero 2268. June 1948.

22. Glass, J. S., and O'Hara, F.: Helicopter Blind Flying, Interim Note on Tests on Hoverfly I. A. F. E. E. Report No. Rota 4. 20 August 1948. Confidential.

23. Stewart, W., and Sissingh, G. J.: Dynamic Longitudinal Stability Measurements on a Single-Rotor Helicopter (Hoverfly Mk. 1). British R.A.E. Report No. Aero 2244. February 1948. Restricted.

24. Zbrozek, J. K.: Introduction to Dynamic Longitudinal Stability of Single-Rotor Helicopter with Hinged Blades. British R.A.E., Report Aero 2248. February 1948. Restricted.

25. Stewart and Brotherhood: Blind Flying Trials on the Hoverfly I Helicopter. British R.A.E Report No. Aero 2283. August 1948. Restricted.

26. Drees, Ir. J. Meijer: A Theory of Airflow Through Rotors and Its Application to Some Helicopter Problems. Journal of the Helicopter Association of Great Britain, pp. 79-104. 1948.

27. Sissingh, G. J.: Survey on German Research and Development of Rotary Wing Aircraft. Armed Services Technical Information Agency, Reports and Translations No.: 1022. 15 August 1948.

- 1949 -

1. Miller, R. H.: A Method for Improving the Inherent Stability and Control Characteristics of Helicopters. Written: January 1949. Journal of Aero. Sciences. June 1950.

2. Gustafson, Amer, Haig, and Reeder: Longitudinal Flying Qualities of Several Single-Rotor Helicopters in Forward Flight. NACA TN 1983. November 1949.

3. Gessow and Amer: An Introduction to the Physical Aspects of Helicopter Stability. NACA TN 1982. Also TR 993. November 1949.

4. Slaymaker, S. E., Lynn, R. R., and Gray, R. B.: Experimental Investigation of Transition of a Model Helicopter Rotor from Hovering to Vertical Autorotation. Written: December 1949. NACA TN 2648.

5. Sullivan, R.: Horizontal Stabilizer for H-5 Aircraft with Litters. Sikorsky Report SER-1933. 25 August 1949.

6. Reeder, J. P., and Haig, C. R.: Some Tests of the Longitudinal Stability and Control of an H-13B Helicopter in Forward Flight. NACA RM L9E25a. 1 August 1949.

7. Beebe, J., and Bradshaw, H. R.: Wind Tunnel Tests of a 0.10 Scale HRP-2 Helicopter Without Rotors, Part I. David Taylor Model Basin Report C-246. August 1949.

8. Beebe, J., and Bradshaw, H. R.: Wind Tunnel Tests of a 0.10 Scale HRP-2 Helicopter Without Rotors, Part II. David Taylor Model Basin Report C-246. October 1949.

9. Harriman, T. J.: Miscellaneous Flight Characteristics of the Model 47 Helicopter. Fifth Annual Forum, A. H. S. 12 May 1949.

10. Mazur, J. W.: Flight Testing of Helicopters by the U. S. Navy. Fifth Annual Forum, A. H. S. 12 May 1949.

11. Cobey, W. E.: Report on the Stability of the Helicopter as Compared with the Autogiro. Prewitt Aircraft Company, Report No. 27-98-3. 20 April 1949.

12. Johnson, W. C.: Theoretical Stability and Control Study for R-5 Helicopters. Goodyear Aircraft Report No. GER-2005. 1 February 1949.

13. Zbrozek, J. K.: The Simple Harmonic Motion of a Helicopter Rotor with Hinged Blades. British R. A. E. Report No. Aero 2319. April 1949.

14. Young, R. A.: Helicopter Engineering. The Ronald Press, New York, 1949.

15. Zbrozek, J. K.: Stability and Control of Single Rotor Helicopter with Hinged Blades. Aircraft Engineering, p. 32. February, 1949.

16. Beebe, John, and Kuldell, P. D.: Wind Tunnel Tests of a 0.10 Scale Model of the HRP-2 Helicopter Without Rotors - Part II - Longitudinal and Lateral Characteristics with Revised Afterbody. David W. Taylor Model Basin Report. October 1949. Restricted.

17. Brotherhood, P., and Burle, M. P.: Flight Measurements of Longitudinal and Lateral Trim of the S-51 Helicopter. British R.A.E. T.N. No. Aero 2020. September 1949. Restricted.

18. Stewart, W.: Notes on Helicopter Approach in Blind Flying Qualities. British R.A.E. TN No. Aero 2030. November 1949. Restricted.

19. Beebe, J., and Bradshaw, H. R.: Wind Tunnel Tests of a 1/7 Scale Model of the XHJP-1 Helicopter Fuselage. David Taylor Model Basin Report C-245, Aero 773. July 1949. Restricted.

20. Beebe, J., and Henkels, W. J.: Wind Tunnel Tests of a 1/10 Scale Model of the HRP-1 Helicopter Without Rotors. David Taylor Model Basin Report C-282, Aero 782. November 1949. Restricted.

21. Guarino, L. S.: Report on Plan for Helicopter Automatic Pilot. Naval Air Material Center, Report Number NAES-INSTR 40-49. 6 June 1949. Restricted.

22. Cobey, William E.: Stability Concepts. Prewitt Aircraft Company, Report Number 26-98-1. 14 January 1949. Restricted.

23. Nickerson, Congdon, Mazur, and others: Limited Tests Proje . TED No. PTR AC-403 Conducted on Model "O3S-1 Helicopter. Naval Air Test Center, Flight Test Division PT36-125. 28 October 1949.

- 1950 -

1. Britland, C. M., and Fail, R. A.: Preliminary Measurements of the Aerodynamic Damping in Pitch of a 12 foot diameter Helicopter Rotor. British A.R.C. Current Paper No. 22, TN Aero 2049. May 1950.

2. Amer, K. B.: Theory of Helicopter Damping in Pitch or Roll and a Comparison of Flight Measurements. Written: 15 May 1950. NACA TN 2136.

3. Carpenter, P. J., and Paulnock, R. S.: Hovering and Low-Speed Performance and Control Characteristics of an Aerodynamic Servocontrolled Helicopter Rotor System as Determined on the Langley Helicopter Tower. NACA TN 2086. May 1950.

4. Cannon and Niehaus: Practical Instrument Flying in the Helicopter. Aeronautical Engineering Review, p. 22. June 1950.

5. Smith, C. C.: Static Directional Stability of a Tandem-Helicopter Fuselage. NACA RM L50F29. 9 August 1950.

6. Gessow and Amer: An Explanation of Some Important Stability Parameters that Influence Helicopter Flying Qualities. Aeronautical Engineering Review, p. 28. August 1950.

7. Bureau of Aeronautics: Bureau of Aeronautics Specification for the Aerodynamic, Structural, and Power-Plant Requirements for Helicopters. Bureau of Aeronautics, NAVAER SR-189. 1 August 1950. Restricted.

8. Hohenemser, K.: A Type of Lifting Rotor with Inherent Stability. Journal of Aero. Sci. September 1950.

9. Fay, Capt. J. S.: Some Present and Future Aspects of Helicopter Piloting. Written: 25 November 1950. American Helicopter. June and July 1951.

10. Bennett, J. A. J., and Liptrot, Capt. R. N.: A Bibliography of Rotating Wing Aircraft. Journal of the Hel. Assoc. of G. B., v. 4, no. 3, 1950, pp. 118-133.

11. O'Hara, F.: Flight Testing of Helicopters. Journal of Hel. Assoc. of G. B. Presented: 25 March 1950.

12. Diamond, Biro, and Carnese: Flight Test and Development Program, XHJP-1 Helicopter, Weekly Summary Report 18-T-04. Piasecki Helicopter Corporation, 14 April 1950. Confidential.

13. Diamond, Biro, and Carnese: Flight Test and Development Program, XHJP-1 Helicopter, Weekly Summary Report 18-T-05. Piasecki Helicopter Corporation. 20 April 1950. Confidential.

14. Diamond, Biro, and Carnese: Flight Test and Development Program, XHJP-1 Helicopter, Weekly Summary Report 18-T-07. Piasecki Helicopter Corporation. 4 May 1950. Confidential.

15. Diamond, Biro, and Carnese: Flight Test and Development Program, XHJP-1 Helicopter, Weekly Summary Report 18-T-08. Piasecki Helicopter Corporation. 19 May 1950. Confidential.

16. Diamond, Biro, and Carnese: Flight Test and Development Program, XHJP-1 Helicopter, Weekly Summary Report 18-T-10. Piasecki Helicopter Corporation. 19 May 1950. Confidential.

17. Diamond, Biro, and Carnese: Flight Test and Development Program, XHJP-1 Helicopter, Weekly Summary Report 18-T-13. Piasecki Helicopter Corporation. 1 June 1950. Confidential.

18. Diamond and Zienkor: Flight Test Program - Model HUP-1 Bunc. 124588 - Weekly Summary Report No. 1, Report No. 18-T-37. Piasecki Helicopter Corporation. 5 September 1950. Confidential.

19. Ritchey, Wallace M., Jr.: Stability and Control Tests of the XH-9B Helicopter. Air Materiel Command. 1 March 1950. Restricted.

20. Sissingh, G. J.: The Frequency Response of the Ordinary Rotor Blade, the Hiller Servo Blade, and the Young-Bell Stabilizer. British R.A.E. Report No. Aero 2367. May 1950.

21. Stewart, W.: Helicopter Control to Trim in Forward Flight. British R.A.E. Report No. Aero 2358. March 1950. Restricted.

22. Torry, Congdon, Mazur, and DeLalio: Evaluation of Stability and Control Characteristics of Model HRP-1 Helicopter Bu. No. 111809 with Stabilizer Device. Naval Air Test Center Report FT36-220. 26 December 1950. Restricted.

23. Arnold and Goland: Helicopter Dynamic Stability and Control Studies. Part I - Longitudinal Stability and Control in Hovering and Forward Flight Including the Effects of Blade Flexibility. Cornell Aero Lab., Report No. BB-437-S-1. 29 September 1950.

24. Biro and Carnese: Weekly Summary Report #9 Flight Test and Development Program, XJHP-1 Helicopter. Piasecki Helicopter Corporation, Report No. 18-T-13. 1 June 1950. Confidential.

25. Head and Hohenemser: Detailed Final Report of Research on High Speed Rotary-Fixed Wing Aircraft. Volume III - The Calculated Dynamic Response of a Rotor in Hovering and at High Tip Speed Ratios. McDonnell Aircraft Corporation, Report No. 1782. 3 August 1950. Confidential.

26. Miller, R. H.: Suggestion for a Simplified Approach to the Helicopter Control Problem. Sixth Helicopter Forum, Philadelphia. 1950.

27. Head and Hohenemser: Detailed Final Report of Research on High Speed Rotary-Fixed Wing Aircraft. Volume V - Sample Aircraft Stability and Control Report. McDonnell Aircraft Corporation, Report No. 1967-A. 20 December 1950. Confidential.

28. Vaccaro, J., Jr.: Development of Two Types of a Combined Fuselage and Swash Plate Attitude Indicators for Helicopters. U. S. Naval Air Material Center. April 1950.

29. Gould, Arthur: Transient Responses of an H-13 Helicopter to Longitudinal Stick Pulses as Measured in Flight. Cornell Aero Laboratories, Inc., Report Number TB-641-F-1. 15 November 1950.

30. Brotherhood, P.: Comparison Between the Measured and Estimated Lateral and Longitudinal Characteristics of a Single Rotor Helicopter. British R. A. E. Report No. Aero 2396. September 1950. Restricted.

31. Daunais, Rita M.: Stability and Control Characteristics of the Kaman Servo-Control Helicopter-Part III. Kaman Aircraft Corporation, Report No. 9980. 4 December 1950.

32. Raesler, J. L.: Stability and Control Characteristics of the Kaman Servo-Control Helicopter-Part I. Kaman Aircraft Corporation, Report No. 9980. 15 February 1950.

33. Raesler, J. L.: Stability and Control Characteristics of the Kaman Servo-Control Helicopter-Part II. Kaman Aircraft Corporation, Report No. 9980. 31 May 1950.

34. Bensen, Igor B.: Biased Cyclic Control for H-5 Helicopter. General Electric, Report No. R50GL174. 25 October 1950.

- 1951 -

1. DeVore, G.: A Discussion of CAA Policies, Flight Test Procedures and Civil Air Regulations for Helicopters. Proceedings of the Seventh Annual Forum, A.H.S. 1951.

2. Mazur, J. W.: Demonstration of Helicopters for the U.S. Navy. Proceedings of the Seventh Annual Forum, A.H.S. 1951.

3. Inter Avia: Automatic Control for Helicopters. Inter Avia, v. 6, no. 3, 1951, p. 147.

4. Wilkinson, D. A.: The Performance of a Single Rotor Helicopter Following Power Cut Whilst Hovering. Flight Tests with a Hoverfly I Near the Ground. British A.A.E.E. Res. 259. Date of Tests: October 1950-January 1951.

5. Gustafson, F. B.: Desirable Longitudinal Flying Qualities for Helicopters and Means to Achieve Them. Written: 1 February 1950. Aero Engineering Review, p. 27. June 1951.

6. Coleman, Frank: Automatic Pilots for Helicopters. American Helicopter, p. 11. February 1951.

7. Amer, K. B., and Gustafson, F. B.: Charts for Estimation of Longitudinal Stability Derivatives for a Helicopter Rotor in Forward Flight. NACA TN 2309. March 1951.

8. Rowe, N. E.: Helicopters Applied to Local Air Service Operation - British Experience and Requirements. S.A.E. National Aeronautical Meeting. S.A.E. Preprint No. 615. April 1951.

9. Meyers, D. N., Vanderlip, E. G., and Halpert, P.: A Tested Solution of the Problem of Helicopter Stability and Automatic Control. Aero Engineering Review, p. 27. July 1951.

10. Stewart, W., and Burle, M. F.: Helicopter Rotor Behavior after Engine Failure in Forward Flight. British R.A.E. TN Aero 2119. August 1951.

11. Bramwell, A.R.S., and Sissingh, G. J.: General Handling and Stability Tests on a Helicopter with a Stabilizing Bar (Bell 47D). British R.A.E. Report No. 2434. August 1951.

12. Sissingh, G. J.G Comparison of Helicopter Rotor Model Tests of Aerodynamic Damping with Theoretical Estimates. British R.A.E. TN Aero 2118. August 1951.

13. Reeder, J. P., Whitten, J. B.: Some Effects of Varying the Damping in Pitch and Roll on the Flying Qualities of a Small Single-Rotor Helicopter. NACA TN 2459. Written: 26 September 1951.

14. Amer, K. B.: Some Flying Qualities Studies of a Tandem Helicopter. NACA RM L51H20a. 10 October 1951.

15. Yates, A. H.: Dynamic Stability of the Helicopter: The Equations of Motion. British A.R.C. Current Paper No. 47. 1 November 1951.

16. Aviation Week: Blind Helicopter Flying Techniques. Aviation Week, p. 74. 5 November 1951.

17. Reeder, J. P.: Helicopter Flight Research at NACA, Langley. Fairchild Fund Paper No. AHS-1. December 1951.

18. Nikolsky, A. A.: Helicopter Analysis. John Wiley and Sons, Inc., New York. 1951.

19. Entwistle, F. I.: HO4S-1 Helicopter Operations in the Conduct of Helicopter/Dipping Sonar Tests. Commander Operational Development Force (Op/V109/S68). 16 October 1951. Confidential.

20. Hohenemser and Doblhoff: Summary of Final Report of Research on High-Speed Rotary-Fixed Wing Aircraft, Report No. 2003. McDonnell Aircraft Corporation. 20 January 1951. Confidential.

21. McDonald: Handling Tests with Powered Controls. Westland Sikorsky MK. 1A. A.A.E.E. Report No. 880 (Part I). 14 June 1951.

22. Seckel, E.: Comparison Between the Longitudinal Stability Characteristics of an H-13 Helicopter Equipped with Dry-Friction and Viscous Stabilizer Bar Dampers. Cornell Report No. TG-703-F-1. January 1951.

23. Seckel, E.: Longitudinal Stability Characteristics of a Gyroscopically Stabilized Helicopter in Forward Flight. Air Materiel Command, AF Technical Report No. 6352. March 1951.

24. Sissingh, G. J.: The Effect of Feedback on the Characteristics of the Hiller System for Helicopter Control. British R.A.E TN No. 2096. March 1951. Restricted.

25. Sissingh, G. J.: The Effect of Induced Velocity Variation on Helicopter Rotor Damping in Pitch or Roll. British R.A.E., Technical Note Aero 2132. November 1951.

26. Miller, R. H.: Principaux Facteurs Influencant Les Caracteristiques de Pilotage des Helicopteres. Congres International de Giraviation. 1951.

27. Arnold, Aleck, and Goland: Helicopter Dynamic Stability and Control Studies. Part II - Lateral Stability and Control in Hovering and Forward Flight Including the Effects of Blade Flexibility. Cornell Aero Laboratory, Report No. BB-437-S-2. 1 June 1951.

28. Barnett, C. A.: Liasion Activities at WP-AFB, Dayton, Ohio by Contractors' Personnel. Kellett Aircraft Corporation, Report No. RX-521. January 1951.

29. Davis, W. V., Jr.: Limited Tests Trials Stability and Control Phase, Model HTL-4. U. S. Naval Air Test Center, Flight Test Division, Report No. FT36-174. 17 September 1951. Restricted.

30. Auld, C. D., and Doyle, F. X.: Wind Tunnel Tests of a 1/16 Scale Model of the XH-16 Helicopter Fuselage. Part II - Additional Tests of Modifications to Improve Directional Stability and Pressure-Drop Characteristics of the Forward-Engine, Oil-Cooler, Exhaust-Port. David W. Taylor Model Basin Report No. C-45[illegible] August 1951. Restricted.

31. Pope, L. N.: Wind Tunnel Tests of a 1/16 Scale Model of the XH-16 Helicopter Fuselage. Part I - Directional Stability Characteristics. David W. Taylor Model Basin Report No. C-427. May 1951. Restricted.

32. Daunais, Rita M.: Stability and Control Characteristics of the Kaman Servo-Control Helicopter - Part IV. Kaman Aircraft Corporation, Report No. 9980. 3 April 1951.

33. Collins, R. E.: A Preliminary Analysis of the Stability and Control Characteristics of the Model HOK-1 Helicopter. Kaman Aircraft Corporation, Report No. P-12. 8 October 1951.

34. Gerstenberger, W.: NAES Auto-Pilot Installation - HO4S-1 Helicopter. Sikorsky Aircraft, Report No. SER-2159. 1 March 1951. Confidential.

- 1952 -

1. Seckel, E.: Correlation of Some Longitudinal Dynamic Stability Characteristics of a Bell Helicopter from Theory and Flight Tests. IAS Preprint No. 356. 31 January 1952.

2. Gray, R. B., McCaskill, A. M., Nikolsky, A. A., Poole, A. K., Slaymaker, S. E.: Model Study of Dynamic Stability of Helicopters. Phase I Development of Model and Testing Techniques. Princeton University, Aeronautical Engineering Laboratory, Report No. 190. 1 February 1952. Restricted.

3. Burkam, J. E.: A Simplified Analysis of Helicopter and Automatic Pilot Dynamic Stability. American Helicopter Magazine, P. 8. February 1952. Part II, p. 11, March 1952.

4. Carter, E. S., Jr.: An Analysis of the Helicopter Transfer Function to Predict Achievable Handling Characteristic of the Stabilized Helicopter. Proceedings of the 8th Annual Forum, A.H.S. 16 May 1952.

5. Sissingh, G. J.: Some Remarks on Dynamic Stability of the Helicopter and Characteristics of Gyratory Stabilizing Systems. Proceedings of the 8th Annual Forum, A.H.S. 16 May 1952.

6. Gessow and Myers: Aerodynamics of the Helicopter. The MacMillan Company, New York. 1952.

7. Remark, P. D.: Design, Fabrication, and Flight Test Stabilizing Controller; H-5 Helicopter Servo Rotor Control System. Goodyear Aircraft Corporation Report No. GER-4630. 24 January 1952.

8. Crim, Reeder, and Shitten: Initial Results of Instrument-Flying Trials Conducted in a Single-Rotor Helicopter. Written: 11 March 1952. NACA TN 2721.

9. Guarino, L. S.: Report on Development and Design of Automatic Pilot for Rotary Wing Aircraft. Naval Air Material Center, Report No. NAES-INSTR-18-52. 21 March 1952. Restricted.

10. Mazur, John W.: An Analytical Method for the Determination of the Basic Longitudinal Stability Characteristics of a Conventional Single-Lifting Rotor Helicopter. Naval Air Test Center. 8 July 1952.

11. Mooers, Alden J: Preliminary Flight Testing of a Honeywell Autopilot in a Piasecki XHJP-1 Helicopter. Minneapolis-Honeywell, Preliminary Technical Report AD5046-TR1-1. 28 April 1952. Restricted.

12. Nikolsky, A. A.: A Quantitative Study of the Effect of Large Increase in r.p.m. and Blade Inertia and Hinge Offset on Stability and Control of a Midget Helicopter. Princeton University, Department of Aeronautical Engineering. November 1952.

13. Stewart, William: Some Recent Helicopter Research Investigations. The Helicopter Association of Great Britain. 21 March 1952.

14. Dini, G. E.: Some Notes on the Aerodynamic Servocontrol of Helicopters. L'Aerotecnica, Volume XXXII - N. 2, p. 63. 15 April 1952.

15. Ellis, Charles W.: Effects of Rotor Dynamics on the Automatic Stabilization of Helicopters. Massachusetts Institute of Technology. May 1952.

16. Holman, J. A.: Stabilizing Controller for H-19 Helicopter, Theoretical Stability Analysis. Goodyear Aircraft Corp., R-569. 30 April 1952.

17. Nikolsky, A. A.: The Longitudinal Stability and Control of Single Rotor Helicopters in Autorotative Forward Flight. Princeton University, Aeronautical Engineering Laboratory, Report No. 215. October 1952.

18. Gebhard, J. G.: Stability and Control. Gyrodyne Company of America, Inc., Report 2C-33200-1. 13 January 1952.

19. Saravanos, B.: Helicopters in Free Ground Vibration. Aircraft Engineering, p. 356. December 1952.

20. Stewart, W.: Second Harmonic Control on the Helicopter Rotor. British R. A. E. Report No. Aero 2472. August 1952. Restricted.

21. Goland, Leonard: The Objectives and Methods of Approach for Helicopter Dynamic Stability and Control Research. Princeton University, Helicopter Laboratory, James Forrestal Research Center. 1 December 1952. Restricted.

22. Remark, P. D.: Design, Fabrication, and Flight Test Stabilizing Controller H-5 Helicopter Servo Rotor Control System. Goodyear Aircraft Corporation, Report No. R-542. 24 January 1952.

23. Ellis, C. W.: A Preliminary Report on the Influence of HTK-1 Flight Characteristics on Automatic Flight Control Equipment. Kaman Aircraft Corporation, Report No. SMR 123. 22 October 1952. Restricted.

24. Warsett, P.: Introductory REAC Study of Helicopter Stability and Lagged Rate Autopilot. M-H Aero Technical Report AR 2425H-TR2. 19 August 1952.

25. Warsett, P., and Brown, C. A.: REAC Study of MH-18 Control System Applied to HUP-2 Helicopter, M-H Aero Technical Report AR 2425H-TR3. 5 September 1952. Restricted.

B. BIBLIOGRAPHY OF ROTOR RPM CONTROL

1. Vernon, J.B.: "Flight Tests on Helicopter Experiment Constant Speed Control", Hamilton Std. Rep. HSP-386, 24 March 1944.

2. Lightfoot, R.B.: "Synchronized Throttle and Pitch Control for YR-4 Aircraft", Sikorsky Aircraft Rep. No. SER-42, 5 May 1944.

3. Zins, W.E.: "Fundamental Tests of the General Elec Rotor Governor for Helicopters", AMC Engineering Division (Serial No. TSEPR-593-66-2), 7 March 1946.

4. Silvester, L.M.: "Tests of the Cornell Aeronautica Laboratory Constant Speed Velocity Type Rotor Gover for Helicopters", AMC Engineering Division (Serial No. TSEPR-582-23-2), 22 April 1946.

5. Silvester, L.M.: "Fundamental Tests of Hamilton Standard Propellers Constant Speed Rotor Governor f Helicopters Installed on a YR-4B Helicopter", AMC Eng neering Division Report No. TSEPR-593-66-3, Septemb

6. Gottfried, R.N.: "Fundamental Tests of the Cornell Aeronautical Laboratory Displacement Type Constant Speed Rotor Governor for Helicopters", AMC Engineer Division Report No. TSEPR-582-23-3, 14 February 19

7. Gates, C.: "Instruction Data for Model CAL SR-58 Constant Speed Rotor Control for the YR-6A Helicopte Cornell Aero Lab. Rep. No. BB-385-S-1, 12 December 1

8. Congdon, E.: "Flight Test Governors -1- Hamilton Standard -11- General Electric -111- Techno-Scienti Model YR-5A", Sikorsky Aircraft Rep. No. SER-1548, 15 June 1948.

9. Zeigler, D.D.: "Operational Tests of the Cornell Electrically Operated Throttle Governor Installed on an H-6 Helicopter", AMC Memorandum Rep., Serial No. MCREXB-503-2-1, 3 June 1949.

10. Devillers & DeJessey: "Commande Du Pas General Sur Voilures Tournantes Par Regulateur Preselectif et Asservir", Congres International de Giraviation, 195

11. Burkam, J.: "Selection of Governor System for HUP Helicopter", Piasecki Helicopter Corporation Report R-36, 27 February 1953.